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K. Y. Liu
J. J. Lee

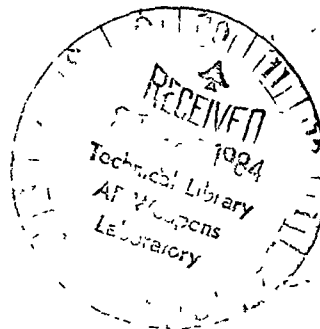
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August 15, 1981

National Aeronautics and
Space Administration

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ABSTRACT

The development of sophisticated adaptive source coding algorithms together with inherent error sensitivity problems fostered the need for efficient space communication at very low bit error probabilities ($\leq 10^{-6}$). This led to the specification and implementation of a concatenated coding system using an interleaved Reed-Solomon code as the outer code and a Viterbi-decoded convolutional code as the inner code. This document presents the experimental results of this channel coding system under an emulated S-band uplink and X-band downlink two-way space communication channel, where both uplink and downlink have strong carrier power. This work was performed under the NASA End-to-End Data Systems program at JPL. Test results verify that at a bit error probability of 10^{-6} or less, this concatenated coding system does provide a coding gain of 2.5 dB or more over the Viterbi-decoded convolutional-only coding system. These tests also show that a desirable interleaving depth for the Reed-Solomon outer code is 8 or more. The impact of this "virtually" error-free space communication link on the transmission of images is discussed and examples of simulation results are given.

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SECTION I

INTRODUCTION

The concatenated coding system was first proposed by Forney (Ref. 1) for the purpose of achieving very low error probabilities. Toward this end, Odenwalder (Ref. 2) proposed a concatenated coding system which uses the Viterbi-decoded convolutional codes as the inner code and the Reed-Solomon (RS) codes as the outer code. A block diagram of such a concatenated coding system is shown in Fig. 1. In this coding system, the incoming data bits are grouped into J -bit symbols and encoded first by an RS encoder. The RS encoder treats consecutive $(2^J - 1 - 2E)$ symbols as the information symbols and generates $2E$ more check symbols. The check symbols are appended to the information symbols to form a $(2^J - 1)$ -symbol RS codeword. This RS codeword structure is shown in Fig. 2. An RS code is usually referred to by its two code parameters, J and E , and denoted as a $(2^J - 1, 2^J - 1 - 2E)$ RS code. The output of the RS encoder is then fed to a convolutional encoder and transmitted through the channel to the receiver. The received data is Viterbi-decoded first and then fed to an RS decoder.

Odenwalder et al. (Ref. 3) later showed by simulation that a $(255, 223)$ RS code concatenated with a constraint length $(K) 7$, rate $(R) 1/2$ or $1/3$, Viterbi-decoded convolutional code is a cost-effective coding system for achieving very low error probabilities. Recently, Rice (Refs. 4, 5, and 6) proposed the use of data compression with adaptive variable-length coding in conjunction with the concatenated RS/Viterbi channel coding system as an alternative for efficient deep space communications. Odenwalder (Ref. 7) presented more simulation results of the concatenated system performance and its sensitivities due to certain factors.

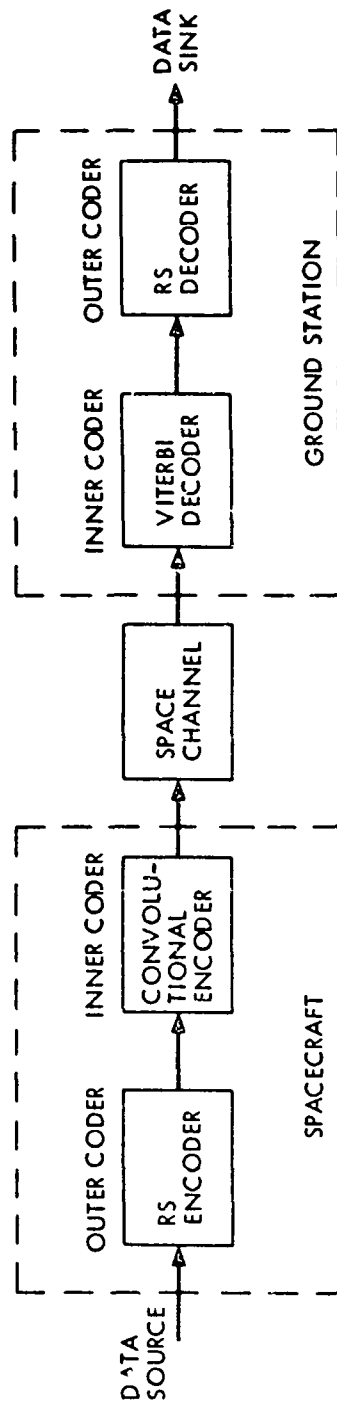
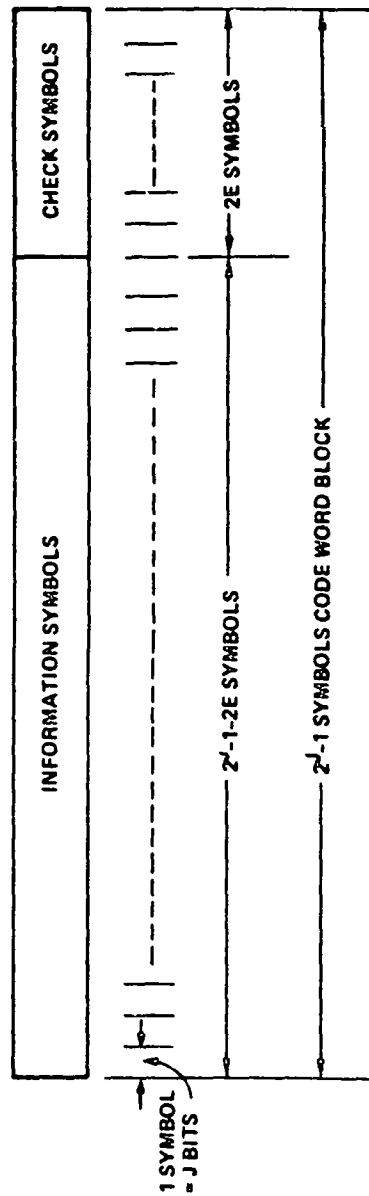


Figure 1. Concatenated Reed-Solomon/Viterbi Coding System Block Diagram



LEGEND J = THE NUMBER OF BITS PER SYMBOL
 $2^J - 1$ = THE NUMBER OF SYMBOLS PER CODE WORD
 E = THE NUMBER OF CORRECTABLE ERRORS
 $2E$ = THE NUMBER OF PARITY-CHECK SYMBOLS

Figure 2. Codeword Structure of an RS Code

In a communication system, the received energy per bit-to-noise spectral density ratio (E_b/N_0) can be expressed as

$$(E_b/N_0) = \left(\frac{P}{N_0} \right) \left(\frac{1}{R} \right)$$

where (P/N_0) is the received signal power-to-noise spectral density ratio and R is the information rate in bits/sec. Hence if one can reduce the (E_b/N_0) required for achieving a given bit error probability, then one can increase the allowable data rate and/or decrease the required transmitter power. The difference between the values of (E_b/N_0) required to achieve the same BER in two channel coding systems is called the coding gain.

The adaptive image compression scheme proposed in Ref. 5 can be applied to a variety of imaging data sources such as Synthetic Aperture Radar (SAR), television camera, and line-scanning imaging devices to significantly reduce the bits required to represent image information. The application of such techniques can thus be used to reduce the power required at the same imaging rate or to increase the imaging rate for the same available power. As an example, the upcoming Galileo mission will use the BARC (Ref. 8) line compression scheme for its imaging data and NOAA will apply a similar approach for communication of IR weather images (Ref. 9).

Adaptive compression algorithms exhibit a classical sensitivity to transmission errors. Hence it is desirable to have a coded channel which provides a very low bit error rate (BER) ($\leq 10^{-6}$) without a corresponding loss in data rate, that is, a coded channel which offers a high coding gain when BER $\leq 10^{-6}$. The concatenated system offers this capability.

The purpose of this document is to present the experimental measurements on the performance of the concatenated RS/Viterbi coding system under an emulated two-way space communication channel with strong carrier power in both uplink and downlink using a test data rate of 40 kbits per second. This work was performed under the NASA End-to-End Data System (NEEDS) program at JPL. These measurements have been undertaken utilizing the facilities at both the Information Processing Research Laboratory (IPRL) and the Telecommunication Development Laboratory (TDL).

The results will show that with an ideal interleaving depth, the concatenated system provides considerable coding gain over the Viterbi-decoded convolutional only coding system at very low bit error probabilities ($\leq 10^{-5}$). The ideal interleaving depth will also be determined. Finally, to exemplify the effect of the "virtually" error-free concatenated coding channel on imaging data, results from simulation runs are given.

SECTION II

EXPERIMENTAL MEASUREMENTS OF A CONCATENATED CODING CHANNEL WITH STRONG UPLINK AND DOWNLINK

For computing the theoretical performance of a concatenated RS/Viterbi channel coding system, both perfect interleaving of an RS code and perfect synchronization in the RS and Viterbi decoders [Refs. 3, 4, 7] were assumed in the existing analytical methods. Let E be the number of symbols an RS code is able to correct. Also let (2^J-1) be the number of symbols in an RS codeword. Then for a perfectly interleaved system the RS decoder output symbol and word error probabilities (SEP and WEP), P_{so} and P_w , can be expressed as

$$P_{so} = \sum_{i=E+1}^{2^J-1} \binom{2^J-1}{i} P_{si}^i (1-P_{si})^{2^J-1-i} \quad (1)$$

and

$$P_w = \sum_{i=E+1}^{2^J-1} \binom{2^J-1}{i} P_{si}^i (1-P_{si})^{2^J-1-i} \quad (2)$$

respectively, where P_{si} is the RS symbol error probability at the RS decoder input.

If the average number of bit errors in each erroneous RS symbol is a constant, then the bit error probability (BEP) P_b at the RS decoder output can be expressed as

$$P_b = \frac{P_e \times P_{so}}{P_{si}} \quad (3)$$

where

$$P_e = f(E_b/N_0) \quad (4)$$

is the bit error probability of the Viterbi decoder under perfect carrier tracking. Thus, once the bit and symbol error probabilities of the Viterbi decoder output are obtained, the bit, symbol, and word error probabilities of the concatenated system can then be determined by computing (1), (2), and (3). The performance obtained using the above assumptions of a perfect interleaved RS code and a constant bit error per RS input error symbol is useful in determining system tradeoffs. However, for actual system design one has to rely on the experimental method to obtain realistic system performance for various depths of interleaving.

This section describes the objectives of such an experiment, its setup, and the results obtained. The experiment was performed utilizing both the TDL and the IPRL facilities.

2.1 TEST OBJECTIVES

The test objectives of this experiment are:

- (1) To determine the bit and word error probabilities of the Viterbi-decoded convolutional only coding system and the RS/Viterbi coding system under an emulated strong uplink and downlink two-way transmission.
- (2) To compare the coding gains of the RS/Viterbi coding system with the Viterbi-decoded convolutional-only coding system.
- (3) To test the sensitivities of the factors which affect the RS/Viterbi coding system performance such as the depth of interleaving, convolutional code synchronization, etc.

2.2 TEST PARAMETERS AND ENVIRONMENT

Test parameters and environment are as follows:

- (1) Test data rates = 40 kbits/second.
- (2) A K = 7, rate (R) = 1/2 Viterbi-decoded convolutional code is concatenated with a J = 8, E = 16 RS code, where J is the number of bits in each RS symbol and E is the maximum number of correctable RS symbols.
- (3) Interleaving depth (I) = 2, 4, 8, and 16.
- (4) S-band strong uplink (carrier margin = 75 dB) and X-band strong downlink (carrier loop SNR \approx 15 dB) two-way transmission through a transponder.
- (5) Transponder: MVM second-order phase-locked loop with 18-Hz threshold loop bandwidth ($2B_{LO}$).
- (6) Receiver (carrier tracking loop): BLOCK IV second-order phase-locked loop with 10-Hz threshold loop bandwidth ($2B_{LO}$).
- (7) SDA (subcarrier tracking loop): BLOCK III second-order Costas loop with 0.375-Hz threshold loop bandwidth ($2B_{LO}$).
- (8) SSA (symbol tracking loop): second-order digital data transition tracking loop with 0.005 nominal relative loop noise bandwidth ($2B_L$).
- (9) Telemetry subcarrier frequency: 370 kHz.
- (10) Modulation index varies from 80 to 85°.
- (11) Noise bandwidth used in measuring the receiver input SNR:
11410.02313 Hz
- (12) Test record size: 32640 bits (= 16 RS words).
- (13) Test duration: 80,000 RS words ($= 1.63 \times 10^8$ bits).

2.3 TEST SETUP

The flow diagram of the test setup is shown in Fig. 3. It is used to emulate the concatenated RS/Viterbi coding system as well as the Viterbi decoded convolutional coding system.

2.3.1 Viterbi-Decoded Convolutional Coding System

The test source data are generated by a 2047-bit PN sequence generator and then encoded by a $K = 7$, $R = 1/2$ convolutional coder. The encoded data are modulated onto the subcarrier first and then onto X-band carrier. The carrier reference is derived from an S-band uplink signal. The resulting X-band downlink RF signal is attenuated to emulate the space transmission loss and then received by the carrier tracking loop of the ground receiver.

The input E_b/N_0 is measured at the receiver 50-MHz IF. The receiver output signal is subcarrier-demodulated, symbol-synchronized, and Viterbi-decoded to reconstruct the input PN source data. The reconstructed data are then compared with the delayed PN data to generate a string of bit error. This bit string is divided into 32640-bit (16 RS words) blocks and recorded on a 9-track 800 bpi tape. This bit error pattern essentially characterizes the Viterbi decoded convolutional coding channel.

2.3.2 RS/Viterbi Concatenated Coding System

The concatenated RS/Viterbi coding system is formed by concatenating an outer RS code of interleaving depth I with a Viterbi-decoded inner convolutional code. The test source data are encoded by a software RS coder with $J = 8$ and $E = 16$. A set of various interleaving depths (i.e., $I = 2, 4, 8$ and 16) are used. Each set of RS coded data and the bit string stored on the error pattern tape is bit-by-bit Exclusive-ORed. The resulting data simulates the input to a ground receiving station. This set of data is then deinterleaved and decoded by a

software RS decoder. A comparison is subsequently made between the test source and the decoded data to determine the bit, the symbol, and the word error probabilities of the concatenated coding system. An RS codeword error is declared if more than 16 symbol errors appear in an RS codeword.

The interleaving scheme used for the RS code is the type B interleaving as described in Ref. 4. This interleaving scheme is illustrated by a depth I interleaved RS code array as follows:

	<u>Information Symbols</u>	<u>Check Symbols</u>
Codeword No. 1	$S_1, S_{I+1}, \dots, S_{222I+1},$	$P_1^1, P_2^1, \dots, P_{32}^1$
Codeword No. 2	$S_2, S_{I+2}, \dots, S_{222I+2},$	$P_1^2, P_2^2, \dots, P_{32}^2$
:	:	:
:	:	:
Codeword No. I	$S_I, S_{2I}, \dots, S_{223I},$	$P_1^I, P_2^I, \dots, P_{32}^I$

Each RS code array consists of I RS codewords. The order of symbol transmission is as follows:

$$S_1, S_2, \dots, S_I, S_{I+1}, S_{I+2}, \dots, S_{2I}, \dots, S_{222I+1}, S_{222I+2}, \dots, S_{223I}, P_1^1, P_2^1, \dots, \\ \dots, P_1^I, P_2^1, P_2^2, \dots, P_2^I, \dots, P_{32}^1, P_{32}^2, \dots, P_{32}^I$$

The deinterleaving process is the reverse of the interleaving process. The transmitted symbol sequence is reassembled during the deinterleaving process into an RS code array, and decoding is performed on each RS codeword in the array. One advantage of this interleaving scheme is that data symbols are transmitted in their natural order. Hence, the data received by the receiver can be used for real-time analysis without any preprocessing. Another advantage of this

interleaving scheme is that storage for information symbols is not required in the encoder.

2.4 TEST RESULTS

Performance tests were made to determine the performance of the Viterbi-decoded convolutional-only coding system and the RS/Viterbi coding system under a two-way transmission, with strong carrier power in both uplink and downlink. A Linkabit LV7035 $R = 1/2$ and $1/3$ $K = 7$ Viterbi decoder with a 64-bit path memory was used in these tests. The resulting test data are plotted in Figs. 4 and 5. An overhead cost of 0.6 dB was added to the E_b/N_0 required by the RS/Viterbi coding system to account for the 12.45% redundancies of the RS parity-check symbols. Note that a concatenated RS/Viterbi coding system has a very steep performance curve. Therefore, it does not have a graceful degradation in performance as in the case of a convolutional-only coding system. In Fig. 4, the coding gain of the RS/Viterbi coding system over the Viterbi-decoded convolutional-only coding system for $BER = 10^{-6}$ appears, where the coding gain is defined as the difference between the values for the E_b/N_0 required to achieve the same BER in these two systems. With an ideal interleaving, the RS/Viterbi coding system has a coding gain of 2.5 dB over the Viterbi-only coding system.

An important parameter in designing a concatenated RS/Viterbi channel coding system is the depth of interleaving. If a small interleaving depth is used, then one has to increase E_b/N_0 to achieve the desired performance. On the other hand, if a large interleaving depth is used, then one is required to include proportionately more memory in the RS encoder (Ref. 11) and decoder. Of course, the magnitude of an ideal interleaving depth depends on the burst characteristics of a Viterbi decoder. Burst errors appear at the output of a Viterbi decoder because of channel noise or incorrect node synchronization. Channel noise

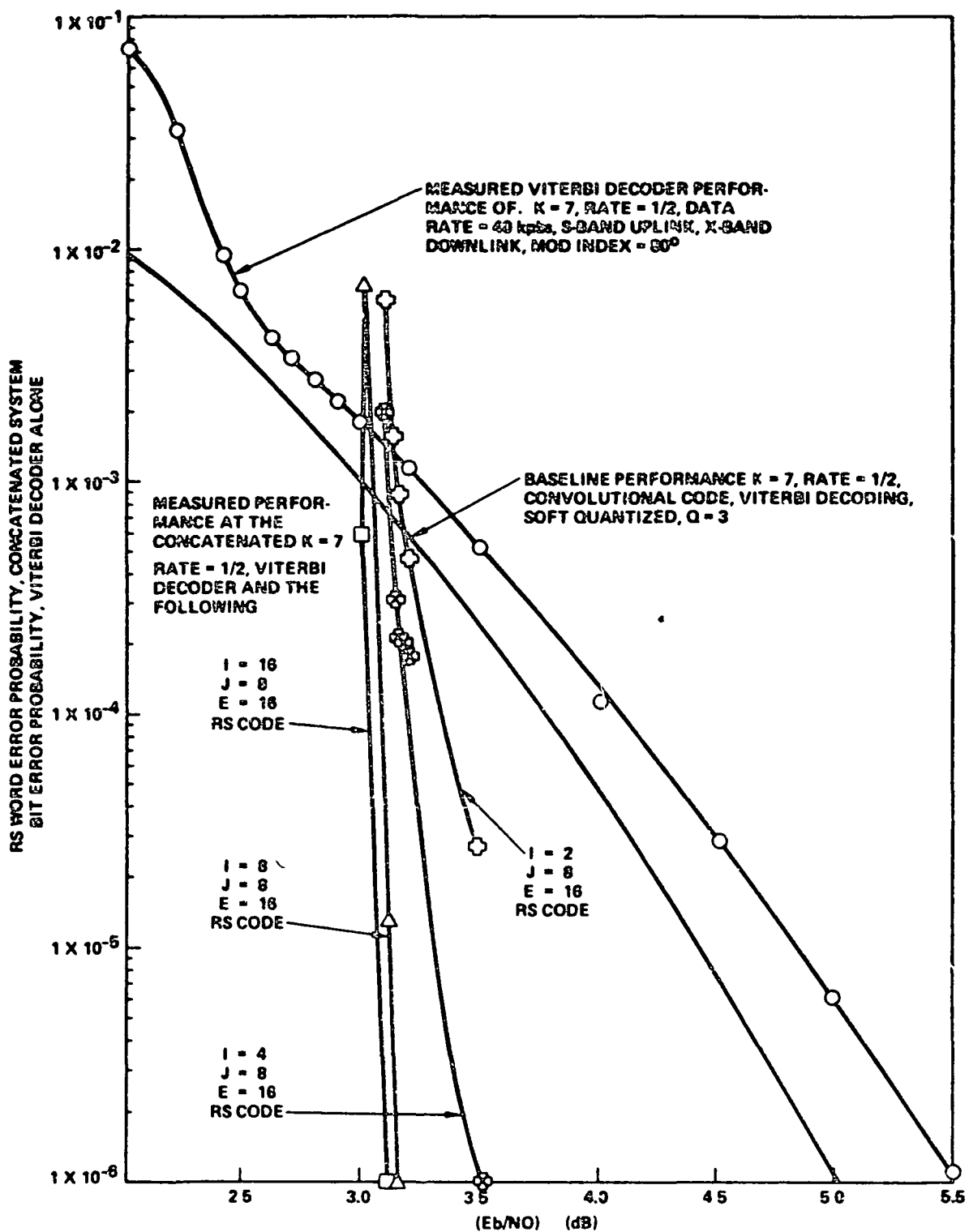


Figure 4. RS/Viterbi Concatenated Code Word Error Probability Versus (E_b/N_0) Performance

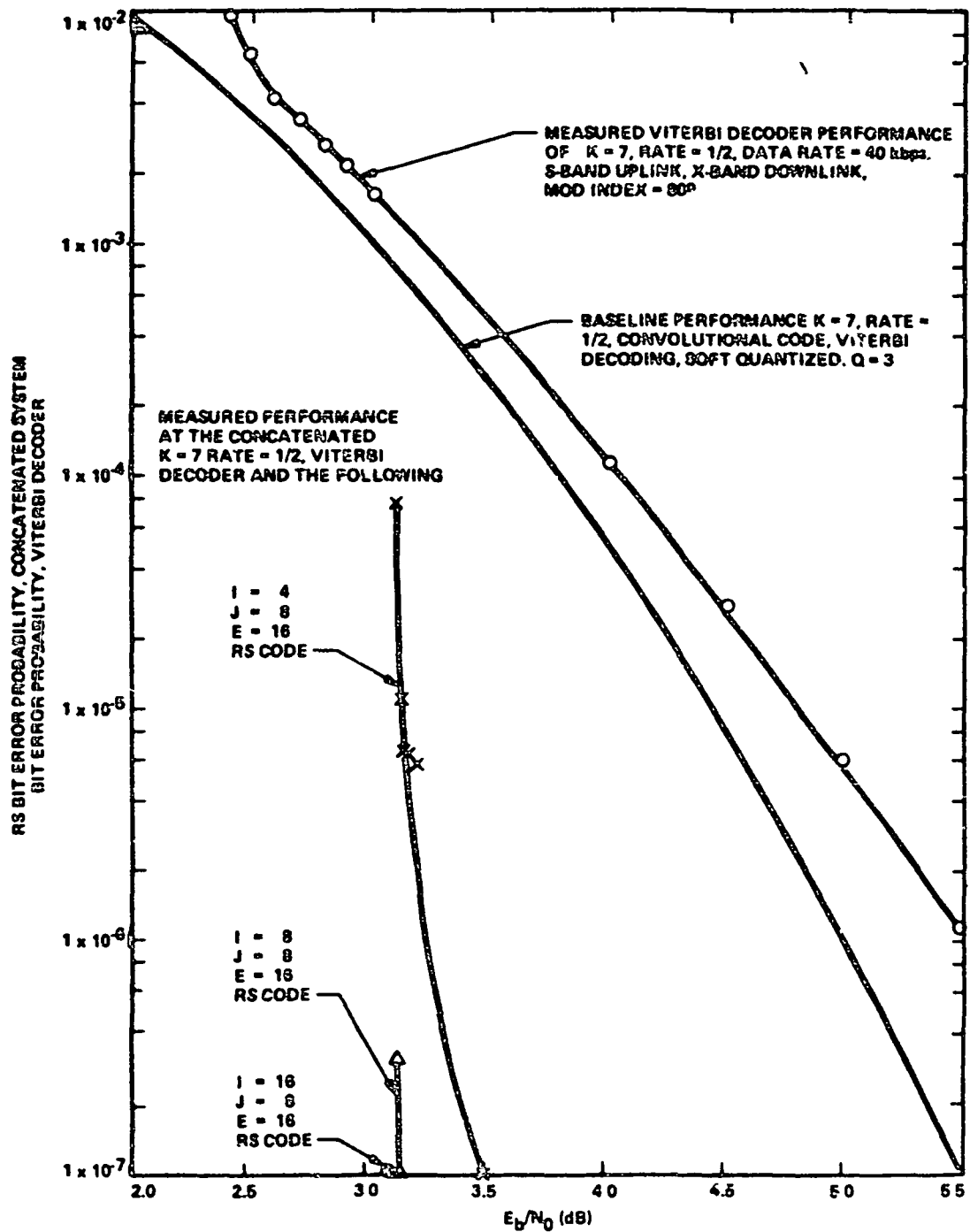


Figure 5. RS/Viterbi Concatenated Code Bit Error Probability Versus (E_b/N_0) Performance

usually causes an incorrect decision in the decoding path that could result in a burst error on the order of 2 to 3 times the constraint length. An incorrect decision as to which symbol is the first code symbol in the received convolutional encoded data also results in a burst error. The process of deciding which symbol is the first symbol in a convolutional code is called the node synchronization process. The node synchronization process may require on the order of 100 bit times. Consequently, large interleaving depths which provide the time division multiplexing are required to spread out the long burst generated by this node synchronization process.

Since node synchronization could seriously affect the concatenated RS/Viterbi channel coding performance, the number of times node resynchronization occurred during tests was also monitored. The node resynchronization threshold has been observed to be around 2.5 dB in E_b/N_0 . Below this threshold, many node resynchronizations may take place. Hence the Viterbi decoder performance curve does not follow the theoretical curve in this region (see Fig. 4). In these tests, the Viterbi decoder was operated near 2.5 dB ($BER \approx 5 \times 10^{-3}$). Hence many occurrences of node resynchronization were observed. Consequently an interleaving depth of 8 or more is needed to achieve ideal channel performance. However, if the Viterbi decoder is operated at 2.6 dB, which is 0.1 dB higher than the node synchronization threshold, with $BER \approx 4 \times 10^{-3}$, then an interleaving depth of 5 is sufficient to achieve a BER of 10^{-6} on the concatenated system output. Of course, one can also use a Viterbi decoder with a lower node synchronization threshold to alleviate the above problem. In this case, one may be able to operate the Viterbi decoder at an E_b/N_0 lower than 2.5 dB while still using a reasonably large interleaving level, say 5 or 8, on the outer RS code.

Since a lower E_b/N_0 will cause the data tracking loop to have a big jump in radio loss at very low E_b/N_0 , this approach will not have significant gain in terms of E_b/N_0 , although it provides a better RS code synchronization performance (Refs. 4 and 7).

The use of a more powerful convolutional code in a concatenated RS/Viterbi coding system has been considered in Refs. 3 and 7. One approach is to use a $K = 7$, $R = 1/3$ rather than a $K = 7$, $R = 1/2$ convolutional code in a concatenated coding system. The theoretical performance obtained when a $K = 7$, $R = 1/3$ convolutional code is used in a concatenated coding system appears to be better than that obtained when a $K = 7$, $R = 1/2$ convolutional code is used (Refs. 3 and 4). However, since a $R = 1/3$ convolutional code compared to a $R = 1/2$ convolution code has a 2 dB loss in symbol energy-to-noise ratio in the data tracking loop, its 0.3 dB gain is entirely lost in the data tracking loop when operated at low E_b/N_0 . This fact was verified through tests. Another approach is to use a $R = 1/2$ convolutional code, with a larger constraint length, say 10, in a concatenated coding system to get more coding gain. Again, the big jump in radio loss of the data tracking loop when operated at low E_b/N_0 will significantly reduce the coding gain. Therefore, end-to-end considerations must be carefully given when this approach is used.

SECTION III

EFFECTS OF THE CONCATENATED CODING SYSTEM ON SPACE COMMUNICATIONS

As shown from the test results in Section II, a concatenated coding system with an ideal interleaving depth provides a "virtually" error free communication channel. This fact assures that a BER of 10^{-5} or less, as generally required for science data of space flight missions, is practically achievable. Since a "virtually" error-free channel is feasible, any sophisticated adaptive source coding algorithms can be applied to both the science/engineering and imaging data without concern as to the error sensitivity problem associated with compressed data.

Figure 6 is a Voyager image which was used as the test image. When this image is transmitted through an emulated space communication channel with a Viterbi-decoded convolutional-only coding system (having a BER ranging from 5.53×10^{-3} to 1×10^{-5}), the resulting images are shown in Figs. 7 to 15. The speckles are due to errors which have occurred during transmission. The output pixel error rate (PER) versus the input BER for the Viterbi channel without image compression is shown in Fig. 16. When the outer RS code is added and a concatenated coding system is thereby formed, the resulting images on the output of this system are as shown in Fig. 17 for the case of $\text{BER} = 5.53 \times 10^{-3}$ with $I = 1, 2, 4, \text{ and } 5$, respectively. Note that in Fig. 17(d), where the concatenated system is implemented with $I = 5$ or more, a faithfully reproduced image is obtained.

From Fig. 15, one can see that a channel bit error probability of 10^{-5} is marginally acceptable for producing high-quality uncompressed image. At this bit error probability the concatenated RS/Viterbi channel has a 1.7-dB coding gain over the Viterbi channel. It is desirable, however, to have a lower channel bit error probability, say 10^{-6} , to improve the image quality. At this bit error

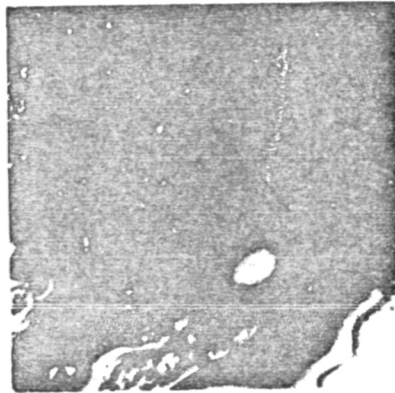


Figure 6. Voyager's Jupiter Image



Figure 7. Simulated Jupiter Image Return Corrupted by the Viterbi Decoded Convolutional Coding Channel ($BER = 5.53 \times 10^{-3}$)

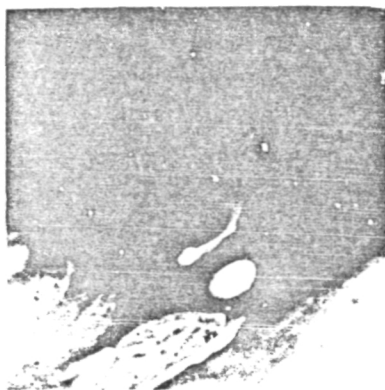


Figure 8. Simulated Jupiter Image Return Corrupted
by the Viterbi Decoded Convolutional
Coding Channel ($\text{BER} = 2 \times 10^{-3}$)



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Figure 9. Simulated Jupiter Image Return Corrupted
by the Viterbi Decoded Convolutional
Coding Channel ($\text{BER} = 1 \times 10^{-3}$)

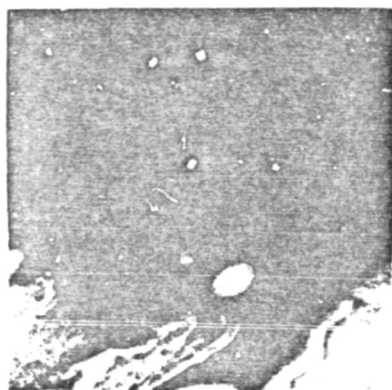


Figure 10. Simulated Jupiter Image Return Corrupted
by the Viterbi Decoded Convolutional
Coding Channel ($\text{BER} = 5 \times 10^{-4}$)

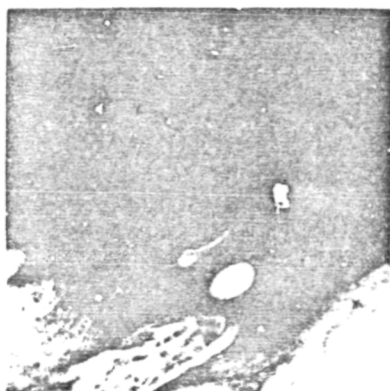


Figure 11. Simulated Jupiter Image Return Corrupted
by the Viterbi Decoded Convolutional
Coding Channel ($\text{BER} = 3 \times 10^{-4}$)

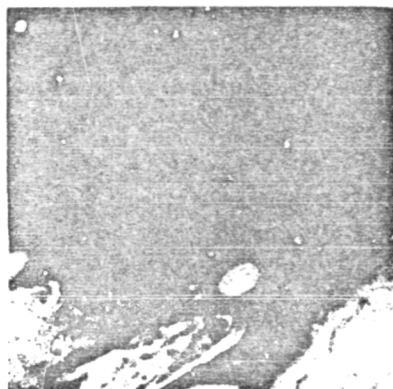


Figure 12. Simulated Jupiter Image Return Corrupted by the Viterbi Decoded Convolutional Coding Channel ($BER = 1 \times 10^{-4}$)

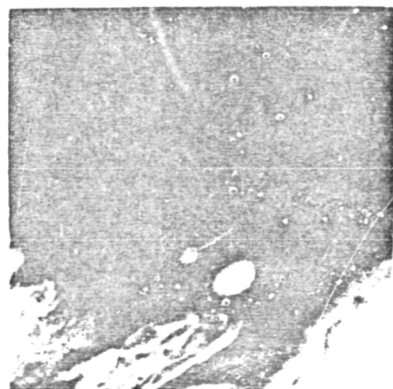


Figure 13. Simulated Jupiter Image Return Corrupted by the Viterbi Decoded Convolutional Coding Channel ($BER = 5 \times 10^{-5}$)



Figure 14. Simulated Jupiter Image Return Corrupted by the Viterbi Decoded Convolutional Coding Channel ($\text{BER} = 3 \times 10^{-5}$)

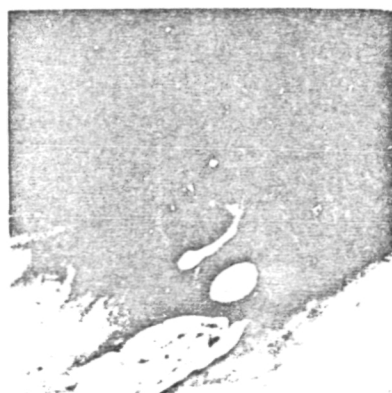


Figure 15. Simulated Jupiter Image Return Corrupted by the Viterbi Decoded Convolutional Coding Channel ($\text{BER} = 1 \times 10^{-5}$)

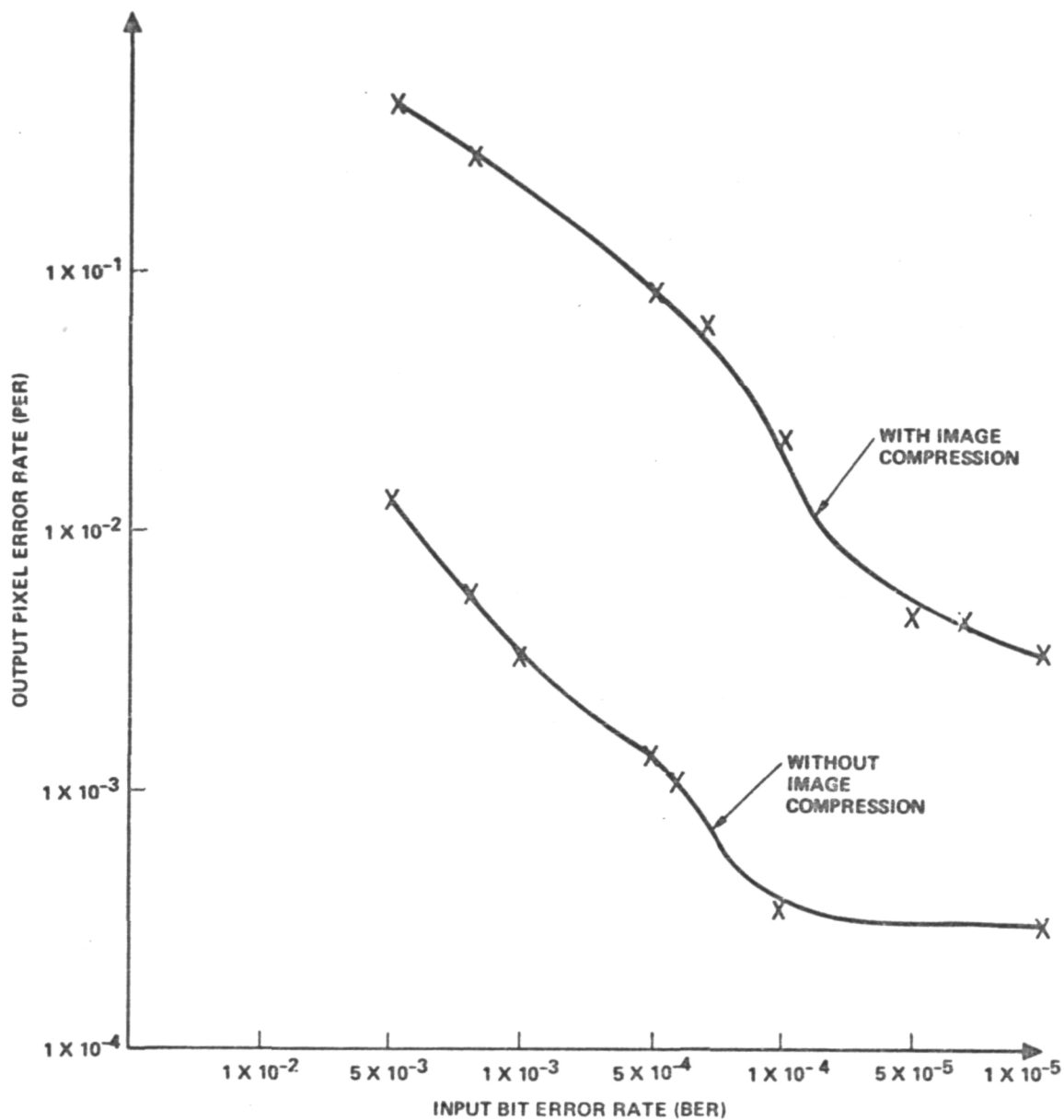
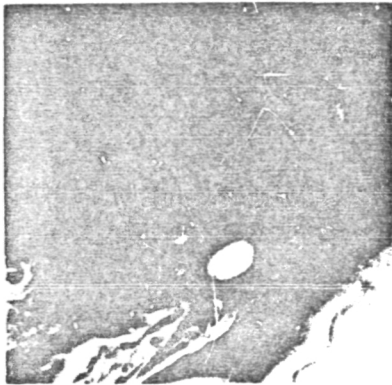


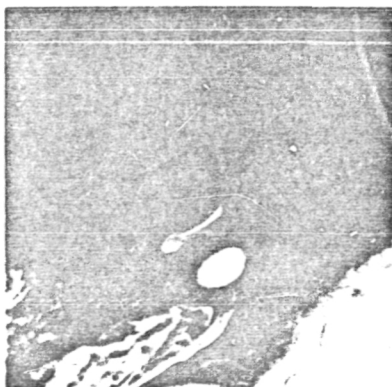
Figure 16. Output Pixel Error Rate (PER) Vs. Input Bit Error Rate (BER) for a Viterbi-Decoded Convolutional Only Coding System.



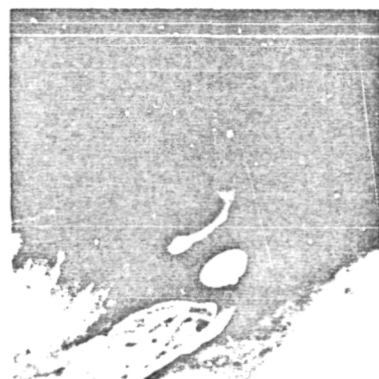
(a) $I = 1$



(c) $I = 4$



(b) $I = 2$



(d) $I = 5$

Figure 17. Simulated Jupiter Image Return Through the Concatenated Coding Channel with $BER = 5.53 \times 10^{-3}$ (No Image Data Compression).

probability the concatenated RS/Viterbi channel has a 2.5-dB coding gain over the Viterbi channel.

In Ref. 8, the Block Adaptive Rate Controlled (BARC) data compression algorithm is proposed. The basic idea of BARC is to partition a line of image data into small data blocks and then use sample-to-sample variation in these blocks as an "activity measure" to determine which block should receive reductions in data quantization. Reduction in quantization are first applied to blocks of higher activity. The reconstructed images using the BARC data compression algorithm with a compression ratio of 2 are shown in Figs. 18 to 26 for various Viterbi decoder output BER's ranging from 5×10^{-3} to 1×10^{-5} . At a compression ratio of 2, the BARC algorithm allows exact reconstruction of the original Voyager image provided there are no transmission errors. The blemish lines in Figs. 18 to 26 are due to the effect of transmission errors on the decompression algorithm. A synchronization on the line basis is also assumed here. The output pixel error rate (PER) versus the input BER for the Viterbi channel with image compression is also shown in Fig. 16.

Using the concatenated channel with $I = 1$ reduces the number of affected lines to as few as shown in Fig. 27. With an interleaving depth of 2 (4), all but three (one) of the lines are reproduced without error as shown in Figs. 27(b) and 27(c). With $I \geq 5$, the output BER becomes less than 10^{-6} and hence all image lines are fully reconstructed without any degradation (see Fig. 27(d)). Thus the concatenated RS/Viterbi coding system does provide an error-free channel for systems with data compression. Also note that since the concatenated RS/Viterbi channel has a very steep performance curve (see Figs. 4 and 5), within 0.1 dB from the threshold BER of 5×10^{-3} on the Viterbi decoder output, the compressed image could be completely corrupted by transmission errors. Assume a BER of 10^{-5} on the Viterbi-decoded convolutional-only coding system

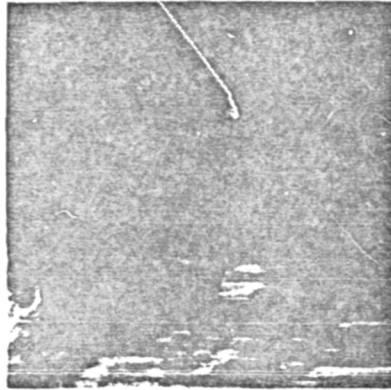


Figure 18. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi Decoded Convolutional Coding Channel (BER = 5.53×10^{-3})

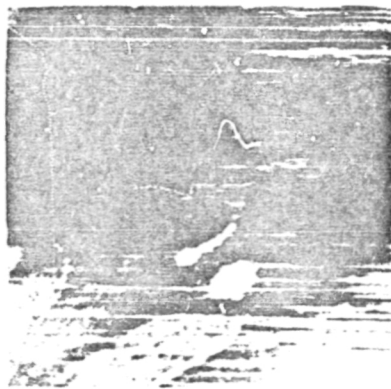


Figure 19. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi Decoded Convolutional Coding Channel (BER = 2×10^{-3})

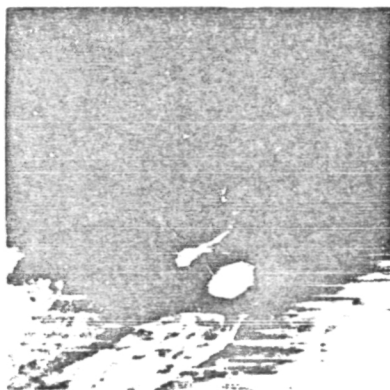


Figure 20. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi Decoded Convolutional Coding Channel (BER = 1×10^{-3})



Figure 21. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi Decoded Convolutional Coding Channel (BER = 5×10^{-4})

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OF POOR QUALITY

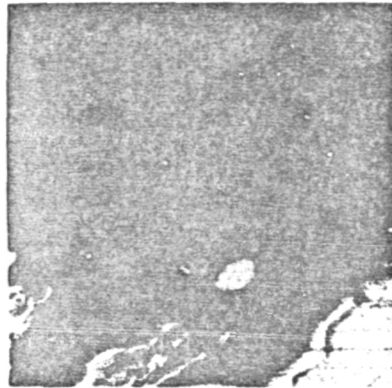


Figure 22. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi Decoded Convolutional Coding Channel (BER = 3×10^{-4})

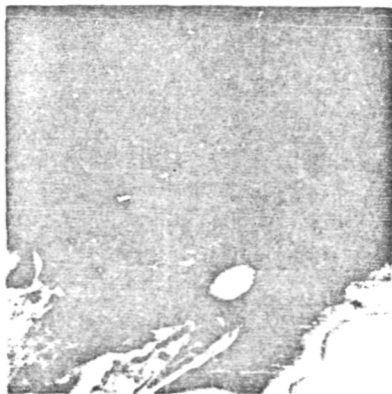


Figure 23. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi Decoded Convolutional Coding Channel (BER = 1×10^{-4})

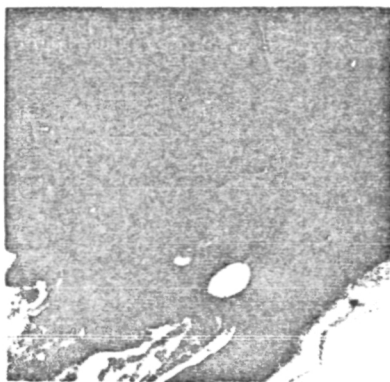


Figure 24. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi Decoded Convolutional Coding Channel (BER = 5×10^{-5})



Figure 25. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi Decoded Convolutional Coding Channel (BER = 3×10^{-5})

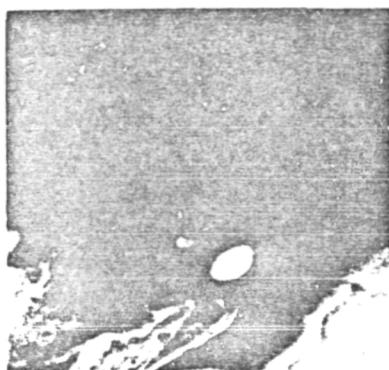
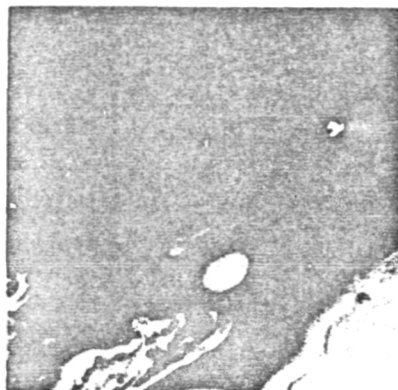


Figure 26. Simulated Jupiter Image Reconstructed From Decompressed Data as Corrupted by the Viterbi-Decoded Convolutional Coding Channel (BER = 1×10^{-5})



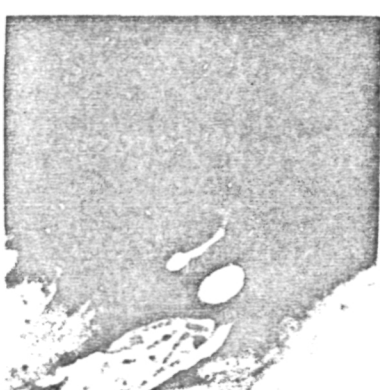
(a) $I = 1$



(c) $I = 4$



(b) $I = 2$



(d) $I = 5$

Figure 27. Simulated Jupiter Image Reconstructed from Decompressed Data Through the Concatenated Channel with BER = 5×10^{-3}

output is marginally acceptable for producing high-quality uncompressed images, then the 2.5 dB coding gain of the concatenated RS/Viterbi channel at $\text{BER} = 10^{-6}$ over the Viterbi channel plus the 3-dB gain of using a data compression ratio of 2 minus the 0.7 dB loss (for the need to operate at $\text{BER} = 10^{-6}$ rather than 10^{-5} to incorporate data compression) will result in a 4.8 dB total gain. This 4.8 dB gain will convert to an improvement of 3 times in data return rate. This improvement in data return rate becomes 3.55 times if a comparison is made for the case where a BER of 10^{-6} is required in both the Viterbi channel, where no data compression is applied, and the concatenated RS/Viterbi channel with data compression.

SECTION IV

CONCLUSIONS

The performance of the concatenated RS/Viterbi channel coding scheme has been evaluated experimentally under a strong uplink and downlink condition. The experimental results showed that the concatenated coding scheme provides a coding gain of 2.5 dB or more at very low bit error rate ($\leq 10^{-6}$) when compared with the Viterbi-decoded convolutional-only system.

Under this channel coding system, a "virtually" error-free channel system is thereby readily obtainable. It provides the basis for the use of any sophisticated source coding schemes such as the BARC and the RM2 (Refs. 4, 5, and 6). For the purpose of demonstrating the effect of the "virtually" error-free communication system, simulation runs on a Voyager image have been performed. The BARC (Ref. 8) was used as the source coding algorithm for the demonstration. Simulation results show that the concatenated coding system does provide an error-free channel while providing a high coding gain and, therefore, any sophisticated source coding scheme is applicable.

In Ref. 10, it was shown that for the nonideal receiver case the concatenated RS/Viterbi channel coding system has even more significant coding gains than the Viterbi-decoded convolutional-only coding system at very low bit error probability ($\leq 10^{-6}$). Hence the concatenated RS/Viterbi channel coding system is a very powerful scheme for achieving error-free space communications.

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